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Quantifying Benefits of Signal Timing Maintenance and Optimization using both Travel Time and Travel Time Reliability Measures

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Quantifying Benefits of Signal Timing Maintenance and Optimization Using both Travel Time and Travel Time Reliability Measures

by

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ABSTRACT

Maintaining and optimizing signal timing directly contributes to an improved end-user driving experience. With recent developments in crowd-sourced vehicle probe data, travel time improvements associated with signal re-timings can be quantitatively assessed without costly infrastructure.

This study compares the performance of three signal re-timing scenarios—1) pre-maintenance, 2) post-time-of-day and clock maintenance, and 3) post-progression optimization—for the weekday AM peak, mid-day, and PM peak time periods. The percentage of vehicles arriving on green and vehicle travel time distributions were evaluated for each of the tasks in each period. User benefits were then quantified using the travel time data with the mean-variance method to determine the dollar savings for the tasks performed. Signal time-of-day plan maintenance and clock synchronization accounted for some of the travel time benefits, but the savings were less reliable than progression optimization, which improved both travel times and reliability.
MOTIVATION
Quantifying signalized corridor travel time performance generally involves investment in data collection infrastructure, equipment, and manpower. For decades, travel time assessment for a signalized corridor was only possible with manual in-vehicle time keeping, instrumented probe vehicles acting as singular data points to record the trajectory and control delay at every intersection [1], or through the use of videography and manual counting. In 2008, Bluetooth re-identification emerged as a technology that could provide much larger and representative sample sizes using data collection devices placed at strategically instrumented locations along an arterial [2].

There have been many performance measures developed in the last decade to assess arrival characteristics, delay, and travel time through a signalized arterial using high-resolution signal event data [3, 4, 5]. These data are digital logs of controller events, including phase and detector activations, to one-tenth of a second time resolution. However, because these performance measures are developed from the data on an intersection-by-intersection basis, such as arrival on green (AOG) and volume-to-capacity ratio, they do not necessarily capture an individual driver’s direct experience through multiple intersections [6]. More recently, crowd-sourced probe vehicle data has enabled performance assessment of arterials without intrusive infrastructure. The data has gained in both precision and robustness with the ever-growing ubiquity of smart phone adoption [7]. The increased geographic and temporal resolution make crowd-sourced data a valuable emerging resource for evaluating the effects of corridor maintenance and re-timing operations on travel time. Consequently, opportunities have arisen to combine the crowd-sourced travel time data with localized high-resolution signal event data to characterize user improvements using volume-weighted methods [8].

As many agencies struggle with shortfalls in funding, basic signal maintenance tasks such as clock synchronization, detector health, and communication uptime are budgeted according to performance-based, objective and quantifiable methods [9]. On the other hand, for agencies with sufficient communications and central systems already in place, the next logical step is to improve corridor travel performance by optimization heuristics or algorithms [10]. This paper presents a
case study that assesses the incremental improvement in operations associated with signal maintenance and optimization activities that such agencies may routinely undertake.

**STUDY CORRIDOR**

The corridor selected for progression improvement is State Road 37 (SR-37), a heavily-traveled commuting arterial south of Indianapolis (Figure 1a). The corridor is a two-way, four-lane divided highway consisting of twelve signals over 9.3 miles. On the north end, there are four closely-spaced intersections within a half-mile (Figure 1b). One of the intersections includes a two-signal interlocking diamond interchange with I-465. SR-37 near the interchange has an AADT of approximately 34,000 vehicles. The south end of the study corridor terminates at SR-144; the AADT at this location is 27,000 vehicles. Additionally, the signal spacing is increased further to the south (Figure 1c): over one mile separates Fairview Road and Smith Valley Road, and 3.1 miles separate Smith Valley Road and SR-144. The majority of the intersections are eight-phased, with the exception of the I-465 interchange and Harding Street, where a two-phase plan sufficiently operates the T-intersection due to a right-turn-only policy for the westbound approach.

In January 2013, the Indiana Department of Transportation (INDOT) initiated an effort to improve progression statewide for select agency-managed signalized arterials using the link-pivot optimization heuristic [11]. The heuristic leverages vehicle arrival and phase activation data from the high-resolution signal event logs at each intersection to determine offset adjustments that would allow for the greatest number of vehicles arriving during green. SR-37 was selected due to its relatively long corridor consisting of irregular spacing between intersections. The corridor was previously managed by two different agency districts – one district managed the intersections from Pilot Gas to Wicker Road and another district managed the intersections from County Line Road to State Road 144. One year prior to the initiative, the north portion of the corridor had been re-timed without the aid of high-resolution detection data, travel time data, or data-driven optimization heuristics. Since this initial re-timing, signal controller firmware was upgraded to enable the logging of high-resolution signal detection and phase event information for all twelve intersections of the corridor. The data provided an opportunity to objectively improve corridor progression with the north and south sections combined. In addition, advances in crowd-sourced
probe vehicle data saw increases in spatial and temporal fidelity, which allowed for a scalable method of computing arterial travel times based on an average space mean speed [12]. The fusion of the two data sets provided fertile ground for an enhanced implementation and evaluation of the link-pivot combination method heuristic for progression optimization.

The objective of this study is to quantify the improvements of progression optimization and to attribute to the contribution of performing timing maintenance tasks (often a pre-requisite for data-driven optimization heuristics). Performance data associated with each set of tasks are assessed for the following dates:

- January 30, 2013 – original state of system (pre-maintenance);
- February 13, 2013 – maintenance tasks complete (post-maintenance);

**MAINTENANCE ACTIVITIES**

The initial maintenance evaluation includes checking whether controller event logging and vehicle detection are functioning at each intersection. Both features are necessary to characterize the arrival patterns of vehicles at each approach. Furthermore, each signal cabinet requires IP communication over a wide-area network for data retrieval. Network connectivity is not only critical for retrieving controller event data, but is also necessary for uploading controller parameters such as time-of-day plans. Initially, Fairview Road was the only intersection identified in the evaluation as needing network repair. However, during the network repair phase, Harding Street also lost network communications.

An inventory of the detector channel configuration for each intersection is needed for the detector health check and to correlate the channels to phases. In this study, improving arterial progression is the main objective, and consequently the mainline detection is prioritized for evaluation. Table 1 lists the signals on SR-37, their internal identification numbers, approaches, corresponding detectors and phasing setup for the mainline through movements in each direction. This type of signal detector inventory table provides a mapping of detection channels to associate phases for interpreting high-resolution event data, optimize progression, and subsequently analyze vehicle
arrival improvements [5]. Combining phase on/off events with the vehicle arrival times, it becomes possible to determine when a vehicle has arrived during the green or red portion of a phase [5]. In this study, no mainline detection issues were discovered.

Crowd-sourced probe vehicle data, on the other hand, requires no physical network and no detection infrastructure components for arterial travel time assessment. The data are downloaded from a third-party web-based traffic services resource. Each record contains an average speed value in a given direction for a segment of roadway over a one-minute interval. Using this speed value, the space mean speed can be computed over the length of the segment. The SR-37 study corridor comprises six of these segments in each mainline direction. Each of the segments are identified and downloaded for the pre-maintenance, post-maintenance, and post-optimization days, covering 13 hours of data per day.

Time-of-Day Plan Schedule Maintenance

A time-of-day plan is a set of controller timings and parameters enacted during a specific time of a day. The weekday time-of-day plan begin and end times, as well as cycle lengths of each intersection are inspected on February 4, 2013, after communication network maintenance was performed at all intersections. The SR-37 signals predominantly run coordination with vehicle actuation on all phases [13] operation from 0600 to 2200, and fully-actuated operation for other times during weekdays; the exception is the I-465 interchange, which consists of a pair of continuously-coordinated intersections driven by a single controller. Traffic signals south of Wicker Road are also managed separately from the ones to the north because of an agency district boundary.

Figure 2a shows the time-of-day plans for each intersection, with shading indicating the cycle length in use for each corresponding period. From the graph, several time-of-day boundaries and cycle length inconsistencies can be seen on both sides of Harding Street. It can also be seen that coordination on the corridor begins at 0600 for the morning peak, with a consistent cycle length of 120s for all intersections. At 0900, the mid-day plan for the northernmost three intersections operate at 80s cycle lengths, while Harding Street runs a 40s cycle because of two-phased operation. Shorter cycle lengths around the I-465 interchange are used to prevent the build-up of
long queues and subsequent intersection lock-up due to the short signal spacing. South of Harding Street, corridor intersections operate at 120s cycle lengths for the mid-day plan. Although this creates longer queues, given the greater distances between intersections the longer cycle lengths accommodate a greater dispersion of platoons.

For the post-maintenance and post-optimization procedures, different traffic conditions at the north and south ends of the corridor necessitate maintaining all cycle lengths at their original values. Although cycle length consistency is compromised during the mid-day and PM peak periods, the values still allow opportunities for half-cycle or third-cycle coordination [14]. South of Thompson Rd, the transition from the mid-day to PM peak timing plans occurs at 1400; however, from Thompson Road northward, the mid-day plan persists until 1530. Consequently, the end times for these mid-day plans are adjusted to align with the 1400 transition, as shown in Figure 2b. In addition, the PM peak plans for the northern three intersections are extended to 1900 to align with the PM peak plans to the south.

The corridor was monitored over a one-week period after the time-of-day plans were aligned. As part of this monitoring, clock synchronization issues were discovered between February 6 and February 11, using the high-resolution signal controller data. The issues include differences in time zone offsets and clock drifting between signals. Time zone offset inaccuracies do not allow for the correct time-of-day plans to run when they are required. Similarly, clock drifting renders vehicle arrival characteristics to be unpredictable between intersections, due to a difference in the communication systems between the northern and southern portions of the corridor. To the north, the intersections with Pilot Gas, I-465, Thompson Road, and Harding Street synchronize time via a local clock server located at Thompson Road. To the south, the remaining intersections synchronize time via a network connection to a time server at the INDOT Traffic Management Center (TMC). To resolve these clock issues, the northern intersections were configured to synchronize via the same TMC server as the southern intersections.
OPTIMIZATION AND RESULTS

After time-of-day plan and clock maintenance are performed, the link-pivot combination heuristic [11] is used to improve progression on the corridor. Figure 3 shows a screenshot of the web-based application used to run the heuristic. Vehicle detection and phase on and off data from the post-maintenance period are used to compute offset adjustments, with an objective of maximizing AOG. This value is determined from a simulated change in upstream vehicle departure times. Callout (i) shows the resulting offset adjustments needed for each intersection, while Callout (ii) and (iii) indicate the Purdue Coordination Diagrams (PCDs) [5] for the respective before and predicted arrival patterns of the mid-day period for one intersection. The offset adjustments are then added to the existing offset values at each controller and the optimization routine is repeated for each time interval corresponding to a time-of-day plan.

Finally, the high-resolution signal event data and crowd-sourced probe vehicle data are combined to assess post-maintenance and post-optimization vehicle arrival characteristics compared to the pre-maintenance baseline scenario. Using the signal event data, the change in the percent of vehicles arriving during the green portion of the phase (POG) from the pre-maintenance period is computed for all intersections in the corridor. In addition, travel times through the corridor are computed using the crowd-sourced probe vehicle data. Although travel time itself is not an objective of the link-pivot optimization heuristic, it acts as a surrogate metric for assessing progression.

AM Peak

The AM peak vehicle detection counts from the event data are illustrated in Figure 4a for each of the three days of analysis. During the AM peak period, the maintenance tasks improve POG for all northbound and southbound approaches by an average of 1.8 and 1.9 percentage points, respectively (Figure 4b, Figure 4c). The biggest gains are seen at Smith Valley Road for the northbound direction at nearly 18 percentage points, while Fairview Road suffers most from the maintenance by dropping 3.8 percentage points in the northbound direction compared to pre-maintenance. Most of the gains from maintenance activities are in the south portion of the corridor, likely due to the north section being retimed one year prior. The optimization improves the POG by 3 points northbound and 2.9 points southbound over the pre-maintenance baseline averages.
However, percentages of green arrivals after the optimization at Epler Avenue and County Line Road drop 4.9 and 15.7 points, respectively, for the southbound direction. This is due to the tidal nature of vehicles heading northbound on SR-37 during the morning period. As the offsets are optimized at each signal by the heuristic, the predicted AOGs at the upstream and downstream intersections are considered in both directions. By using AOG, the heuristic naturally favors the higher northbound volumes to achieve a greater number of vehicles arriving on green. However, POG assessment is not sensitive to day-to-day volume changes.

Empirical cumulative frequency distribution curves in Figure 4d and Figure 4e are used to characterize the travel times using crowd-sourced probe data for all three scenarios (pre-maintenance, post-maintenance, and post-optimization) in both directions. The median (50th-percentile) northbound post-maintenance travel time improves by 0.9 minutes over the pre-maintenance period, while the post-optimization median travel time improves by 2 minutes. Generally, the overall travel time reliability also increases for the post-optimization scenario, as characterized by a steeper distribution curve. In the southbound direction, only marginal improvements of 0.1 and 0.6 minutes at the median are recorded for the post-maintenance and post-optimization periods, with the post-maintenance period seeing a generally-less reliable travel time distribution.

**Mid-Day**

The mid-day period experiences more modest gains in both POG (Figure 5b, Figure 5c) and reduction in travel time (Figure 5d, Figure 5e). Overall, the corridor gains less than 1 percentage point in both the northbound and southbound POG by maintenance alone. Optimization improves the northbound POG by 3.5 points and the southbound by 1 point. Northbound arrivals see the biggest gain at Smith Valley Road at 11 percentage points after maintenance, but a post-optimization increase of only 10 points, relative to the pre-maintenance period. This has been offset by a slightly higher POG increase in the southbound approach at SR-144 during the same period. The northbound travel time remains unchanged for the post-maintenance period, while seeing a modest improvement of 0.3 minutes post-optimization. The southbound direction had negligible improvements of 0.1 and 0.4 minutes at the median for post-maintenance and post-optimization periods, respectively.
PM Peak
The PM peak period experiences the biggest increase in northbound POG again at Smith Valley Road by 29 points post-maintenance and 28 points post-optimization, as seen in Figure 6b. Overall however, these northbound gains are curbed by POG decreases at Fairview Road for post-maintenance, and I-465 and Epler Avenue for post-optimization. The overall northbound POG increases by 1.8 and 3 percentage points, respectively, for post-maintenance and post-optimization. In the southbound direction, the overall post-maintenance POG remains unchanged, while the post-optimization results improve by an overall 3.4 percentage points, as shown in Figure 6c.

The travel time results during the PM peak period show that for the northbound direction, maintenance improves travel time slightly more than optimization (Figure 6d). The median northbound travel time post-maintenance is 0.7 minutes less than the baseline, while the post-optimization travel time is only 0.5 minutes less. This is due to the optimization heuristic favoring the heavier southbound volumes (Figure 6a) and POG. However, as reflected in the southbound travel time graph in Figure 6e, only marginal improvements of 0.4 minutes resulted from the optimization, with negligible improvements by maintenance alone. For the slowest 20% of travelers, both maintenance and optimization activities increased travel time in the southbound direction compared to the baseline, signifying a reduction in arterial travel time reliability.

Statistical Significance of POG
A statistical test is conducted to determine whether the improvements in POG are significant for post-maintenance and post-optimization from the pre-maintenance baseline for all time periods. A one-sided significance test with consideration to the volume proportions of each scenario is conducted with \( \alpha = 0.05 \). For post-maintenance, nine, five, and eight approaches in the corridor have significant improvements to the POG in the AM peak, mid-day, and PM peak, respectively while three, seven, and twelve approaches have significant worsening of POG performance in the AM peak, mid-day, and PM peak, respectively (Table 2a). For the post-optimization scenario, twelve, ten, and eleven approaches improve in the AM peak, mid-day, and PM peak, respectively while two, seven, and eight approaches worsen in the AM peak, mid-day, and PM peak, respectively (Table 2b). The bulk of improvements from maintenance and optimization occur.
during the AM peak period, while there is more tradeoff between the northbound and southbound approaches for the other two periods.

**USER BENEFIT COST ESTIMATION**

Signal timing maintenance and optimization almost invariably fall under the purview of some public entity, whether it is the state DOT or a local municipal agency. Consequently, there are significant benefits which can be calculated for the progression of vehicles through a corridor. The most commonly considered of these benefits is the reduction in travel time for individual drivers. This time savings can easily be monetized by determining a time value of money for passenger cars and freight vehicles [15].

Traditional user benefit calculations related to travel time savings have focused on the reduction in average or median corridor travel time [16, 17]. However, there is increasing interest from practitioners in also considering the impact of improvements in travel time reliability; that is, a reduction in the variability of travel times around some central value. Prior study has shown that consumers value improvements to travel time reliability at least as much, if not more so, than actual reductions in travel time [18, 19, 20].

In estimating user travel time benefits that result from the post-maintenance and post-optimization scenarios, we incorporate both the monetary value of travel time savings and the value of improvements in reliability, in a method known as the “mean-variance approach.” The mean-variance approach was utilized due to its explicit consideration of both measures of central tendency and dispersion within the travel time distributions. While some measures (such as the travel time/buffer/planning indices) describe travel time variability, they do not adequately convey cases in which both travel time mean and variance are impacted. Similarly, mean-variance does not provide the user with a direct comparison of travel time along the corridor relative to free flow conditions. However, the principal interest in evaluating travel conditions in this study was relative to the different maintenance scenarios, rather than against some baseline performance standard.
The measure for travel time reliability is chosen to be the standard deviation of travel time through the corridor, in line with this methodology [21, 22]. The travel time benefits for passenger and commercial vehicles are computed as:

\[ Benefit_i = TTSV_i + TTRV_i \]  

(1)

Where

- \( Benefit_i \) = total travel time benefits for vehicle type \( i \) ($)
- \( TTSV_i \) = travel time savings value for vehicle type \( i \) ($)
- \( TTRV_i \) = travel time reliability value for vehicle type \( i \) ($)

And

\[
TTSV_i = \Delta TT * Vol * P_i * Occ_i * TTV_i * \frac{1 \, hr}{60 \, min} 
\]  

(2)

\[
TTRV_i = \Delta SD * Vol * P_i * Occ_i * SDV_i * \frac{1 \, hr}{60 \, min} 
\]  

(3)

Here,

- \( \Delta TT \) = The change in mean travel time along the corridor, as measured using crowd-sourced data (min)
- \( \Delta SD \) = The change in the standard deviation of travel time along the corridor (min)
- \( Vol \) = The traffic volume through the corridor during the analysis period, measured using count detectors on the intersection approaches (vehicles)
- \( P_i \) = The percentage of the traffic stream that vehicle type \( i \) comprises
- \( Occ_i \) = The average vehicle occupancy of vehicle type \( i \) (persons)
- \( TTV_i \) = The time value of money for an individual in vehicle type \( i \) ($/person-hr)
- \( SDV_i \) = The monetary value of a unit change in travel time standard deviation for an individual in vehicle type \( i \) ($/person-hr)

In this analysis, two vehicle types are considered: passenger cars and commercial trucks. The value of travel time, as well as the travel time savings estimation methodology are drawn from the latest version of the Urban Mobility Report [23]. At present, the Urban Mobility Report does not provide a direct way to monetize travel time reliability. However, a recent NCHRP report provides a ratio of 1.3 for the value of a unit change in reliability to a unit change in actual travel time [24]. This ratio is applied to the time value of money in the Urban Mobility Report to estimate the monetary...
benefit of a change in travel time reliability. Table 3 provides a summary of the annual estimates of travel time savings for weekday drivers, along with an estimation of the annual user travel time benefits for the post-maintenance and post-optimization scenarios. Generally, it can be seen that the largest user benefits accrue to northbound traffic during the morning period, with annual benefits ranging from $448,241 to $2,311,380.

The impact of increased travel time and variability in certain periods for southbound traffic can also be seen; traffic on the southbound lanes in the evening period saw increases in both average travel times and travel time standard deviations, which is reflected in negative annual benefits (or additional user costs) of $482,398 and $125,754 for post-maintenance and post-optimization, respectively. Overall, however, the benefits of signal maintenance and optimization has a net positive effect, with combined annual benefits for both directions totaling $423,473 for post-maintenance, and $2,989,095 for post-optimization.

Figure 7 provides a further breakdown of the user benefits attributable to changes in travel time and travel time reliability. Here, the column charts show the same “total benefit” values for each time period and direction as presented in Table 3. Additionally, the separate “time savings benefit” and “reliability” benefit are displayed for each case. In Figure 7b for example, it is evident that a majority of user benefits in the corridor were accrued for the northbound direction during the AM period of the post-optimization scenario. Roughly 60% of this benefit was from travel time savings, while the remainder was due to significant increases in travel time reliability (that is, a decrease in standard deviation).

It can also be seen that for a number of other cases, such as the mid-day period of the post-optimization scenario (Figure 7d), travel time reliability comprised a substantial amount of the total user benefit, relative to travel time savings. In several instances, such the southbound lanes during the PM peak period of the post-optimization scenario (Figure 7f), a worsening of travel time reliability actually changed the net user benefit to a negative value, relative to the benefits that resulted only from reductions in travel time.
It can be seen that for the post-maintenance scenario in Figure 7a, the effect of increased reliability for the northbound lanes is modest relative to reductions in average travel time. Conversely, while the southbound lanes see only a slight increase in average travel time, there is a larger increase in travel time variance (standard deviation), with this measure capturing most of the negative benefits as shown in Table 3. For the post-optimization scenario in Figure 7b, it can be seen that the impact of increased travel time reliability for the northbound lanes has nearly the same benefit as the actual travel time savings; for the combined benefits of both directions, increased travel time reliability still carries substantial value to the end user.

CONCLUSIONS

Percentage of vehicles arriving on green and vehicle travel times for a section of SR-37 south of Indianapolis were evaluated for three separate scenarios in 2013. The pre-maintenance baseline data assessed the corridor without changes to signal timing. After the time-of-day plans were aligned and controller clocks were synchronized, the post-maintenance median travel times saw modest reductions in the northbound direction by 0.9 minutes in the AM peak period. The progression-optimized offsets provided the greatest reductions in travel time, with a median of 2 minutes for the northbound AM peak over the pre-maintenance scenario. The improvements to percent of green arrivals were also found to be statistically significant for that period. The PM peak saw a more modest improvement of 0.7 minutes in the northbound direction after optimization. However, both after-scenarios resulted in less reliable travel times for the heavy southbound PM peak flows, especially for the slowest 20% of travelers. There were more tradeoffs in arrivals on green between northbound and southbound approaches throughout the corridor in the PM peak as a result of maintenance and optimization.

Using the mean-variance user benefit calculation method, which accounted for both median travel time and travel time reliability, the user benefit accrued for maintenance-only tasks was $423,473 for all weekdays in one year. Benefits as a result of optimization activities were substantially higher, totaling $2,989,095 for all weekdays in one year. This study has shown that a non-trivial amount of user benefit can be derived simply by performing time-of-day and clock maintenance tasks; additional positive impact can be demonstrated in future research through measures such as
fuel savings and emissions reductions associated with this maintenance. These maintenance activities are also crucial for accurately performing optimization tasks that do not involve new equipment or infrastructure investments. Moreover, progression optimization may come with additional agency time and resource costs which may not be practical at all locations. Future research may leverage methods similar to the mean-variance approach to monetize the value of these maintenance and optimization activities. This valuation, based on objective measures of travel time and travel time reliability improvements, will serve as a strongly defensible metric for continuing the development of integrated signal optimization tasks based on high-resolution controller and crowd-sourced probe vehicle data.

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(a) Corridor location within Indiana.

(b) Northern portion of corridor.

(c) Southern portion of corridor

Figure 1. Map overview.
Table 1. Detection and phasing inventory of study corridor.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Identification No.</th>
<th>Northbound Channels</th>
<th>Northbound Phase</th>
<th>Southbound Channels</th>
<th>Southbound Phase</th>
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</thead>
<tbody>
<tr>
<td>1. Pilot Gas</td>
<td>4493</td>
<td>5, 6, 9</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2. I-465*</td>
<td>2077</td>
<td>37, 38</td>
<td>Overlap B</td>
<td>41, 42, 45</td>
<td>Overlap F</td>
</tr>
<tr>
<td>3. Thompson Rd.</td>
<td>2028</td>
<td>5, 6, 9, 10</td>
<td>2</td>
<td>22, 25, 26</td>
<td>6</td>
</tr>
<tr>
<td>4. Harding St.</td>
<td>2153</td>
<td>2, 5, 6</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>5. Epler Av.</td>
<td>2138</td>
<td>5, 6, 9</td>
<td>2</td>
<td>14, 17, 18</td>
<td>6</td>
</tr>
<tr>
<td>6. Banta Rd.</td>
<td>4414</td>
<td>17, 18</td>
<td>6</td>
<td>19, 20</td>
<td>2</td>
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<tr>
<td>7. Southport Rd.</td>
<td>4437</td>
<td>2</td>
<td>6</td>
<td>13</td>
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<td>8. Wicker Rd.</td>
<td>4443</td>
<td>2, 4</td>
<td>2</td>
<td>8, 10</td>
<td>6</td>
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<td>9. County Line Rd.</td>
<td>4431</td>
<td>9</td>
<td>6</td>
<td>13</td>
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<td>10. Fairview Rd.</td>
<td>4413</td>
<td>10, 11</td>
<td>6</td>
<td>5, 16</td>
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<td>11. Smith Valley Rd.</td>
<td>4469</td>
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<tr>
<td>12. State Road 144</td>
<td>4458</td>
<td>--</td>
<td>--</td>
<td>13, 14</td>
<td>2</td>
</tr>
</tbody>
</table>

* Two intersections using a single controller.
Figure 2. Time-of-day plan compatibility assessment of intersections, shaded by cycle length.
Figure 3. Web-based application to optimize signal offsets for progression.
Figure 4. Changes in performance during the AM peak period (0600-0900).
Figure 5. Changes in performance during the mid-day period (0900-1400).
(a) Number of detections, both directions.

(b) Percent of vehicles arriving on green, northbound.

(c) Percent of vehicles arriving on green, southbound.

(d) Cumulative frequency distributions of travel time, northbound.

(e) Cumulative frequency distributions of travel time, southbound.

Figure 6. Changes in performance during the PM peak period (1400-1900).
### Table 2. Statistical significance (α = 0.05) of changes in POG.

(a) Post-maintenance from pre-maintenance.

<table>
<thead>
<tr>
<th>Approach</th>
<th>AM Peak (0600 - 0900)</th>
<th>Mid-Day (0900 - 1400)</th>
<th>PM Peak (1400 - 1900)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z-Score</td>
<td>P-Value</td>
<td>Improved?</td>
</tr>
<tr>
<td>Pilot Gas (NB)</td>
<td>-1.65142</td>
<td>0.049</td>
<td>No</td>
</tr>
<tr>
<td>I-465 WB Ramp (NB)</td>
<td>-0.24683</td>
<td>0.403</td>
<td>No</td>
</tr>
<tr>
<td>I-465 WB Ramp (SB)</td>
<td>0.20718</td>
<td>0.418</td>
<td>No</td>
</tr>
<tr>
<td>I-465 EB Ramp (NB)</td>
<td>2.95039</td>
<td>0.002</td>
<td>Yes</td>
</tr>
<tr>
<td>I-465 EB Ramp (SB)</td>
<td>-0.27907</td>
<td>0.390</td>
<td>No</td>
</tr>
<tr>
<td>Thompson Rd. (NB)</td>
<td>2.86528</td>
<td>0.002</td>
<td>Yes</td>
</tr>
<tr>
<td>Thompson Rd. (SB)</td>
<td>2.74163</td>
<td>0.003</td>
<td>Yes</td>
</tr>
<tr>
<td>Harding St. (NB)</td>
<td>-1.69198</td>
<td>0.045</td>
<td>No</td>
</tr>
<tr>
<td>Epler Av. (NB)</td>
<td>1.08720</td>
<td>0.138</td>
<td>No</td>
</tr>
<tr>
<td>Epler Av. (SB)</td>
<td>0.24312</td>
<td>0.404</td>
<td>No</td>
</tr>
<tr>
<td>Banta Rd. (NB)</td>
<td>-0.78828</td>
<td>0.215</td>
<td>No</td>
</tr>
<tr>
<td>Banta Rd. (SB)</td>
<td>0.43683</td>
<td>0.332</td>
<td>No</td>
</tr>
<tr>
<td>Southport Rd. (NB)</td>
<td>1.49615</td>
<td>0.067</td>
<td>No</td>
</tr>
<tr>
<td>Southport Rd. (SB)</td>
<td>-0.07790</td>
<td>0.469</td>
<td>No</td>
</tr>
<tr>
<td>Wicker Rd. (NB)</td>
<td>6.26022</td>
<td>0.000</td>
<td>Yes</td>
</tr>
<tr>
<td>Wicker Rd. (SB)</td>
<td>0.03396</td>
<td>0.486</td>
<td>No</td>
</tr>
<tr>
<td>County Line Rd. (NB)</td>
<td>6.07302</td>
<td>0.000</td>
<td>Yes</td>
</tr>
<tr>
<td>County Line Rd. (SB)</td>
<td>-0.25856</td>
<td>0.398</td>
<td>No</td>
</tr>
<tr>
<td>Fairview Rd. (NB)</td>
<td>-4.91025</td>
<td>0.000</td>
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<tr>
<td>Fairview Rd. (SB)</td>
<td>7.37278</td>
<td>0.000</td>
<td>Yes</td>
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<tr>
<td>Smith Valley Rd. (NB)</td>
<td>13.90282</td>
<td>0.000</td>
<td>Yes</td>
</tr>
<tr>
<td>Smith Valley Rd. (SB)</td>
<td>1.82962</td>
<td>0.034</td>
<td>Yes</td>
</tr>
<tr>
<td>SR 144 (SB)</td>
<td>4.86363</td>
<td>0.000</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(b) Post-optimization from pre-maintenance.
Table 3. Tabulation of Annual Travel Time Savings & Annual Travel Time Savings and User Benefits (Travel Time Savings + Travel Time Reliability) for the Post-Maintenance and Post-Optimization Cases

<table>
<thead>
<tr>
<th></th>
<th>Travel Time Saved, Post-Maintenance (veh-min)</th>
<th>User Benefit, Post-Maintenance ($)</th>
<th>Travel Time Saved, Post-Optimization (veh-min)</th>
<th>User Benefit, Post-Optimization ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Northbound</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM Peak</td>
<td>940,431</td>
<td>$448,241</td>
<td>4,497,828</td>
<td>$2,311,380</td>
</tr>
<tr>
<td>Midday</td>
<td>-200,223</td>
<td>($108,394)</td>
<td>559,891</td>
<td>$279,999</td>
</tr>
<tr>
<td>PM Peak</td>
<td>1,033,610</td>
<td>$502,166</td>
<td>703,663</td>
<td>$341,610</td>
</tr>
<tr>
<td>Total Northbound</td>
<td>1,773,817</td>
<td>$842,013</td>
<td>5,761,382</td>
<td>$2,932,989</td>
</tr>
<tr>
<td><strong>Southbound</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM Peak</td>
<td>-86,149</td>
<td>($56,517)</td>
<td>53,406</td>
<td>$10,237</td>
</tr>
<tr>
<td>Midday</td>
<td>225,031</td>
<td>$120,691</td>
<td>360,030</td>
<td>$171,623</td>
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<tr>
<td>PM Peak</td>
<td>-890,832</td>
<td>($482,398)</td>
<td>-134,375</td>
<td>($125,754)</td>
</tr>
<tr>
<td>Total Southbound</td>
<td>-751,951</td>
<td>($418,223)</td>
<td>279,061</td>
<td>$56,105</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM Peak</td>
<td>854,282</td>
<td>$391,724</td>
<td>4,551,234</td>
<td>$2,321,617</td>
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<tr>
<td>Midday</td>
<td>24,807</td>
<td>$12,297</td>
<td>919,921</td>
<td>$451,622</td>
</tr>
<tr>
<td>PM Peak</td>
<td>142,777</td>
<td>$19,768</td>
<td>569,288</td>
<td>$215,856</td>
</tr>
<tr>
<td>Total Combined</td>
<td>1,021,867</td>
<td>$423,790</td>
<td>6,040,443</td>
<td>$2,989,095</td>
</tr>
</tbody>
</table>
Figure 7. Comparison of annual travel time savings benefits, travel time reliability benefits, and total benefits.